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(54) **MONITORING SYSTEM AND METHODS FOR A DISTRIBUTED AND RECOVERABLE DIGITAL CONTROL SYSTEM**

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G06F 11/00 (2006.01)

(52) **U.S. Cl.** **714/10**

(58) **Field of Classification Search** 714/10
See application file for complete search history.

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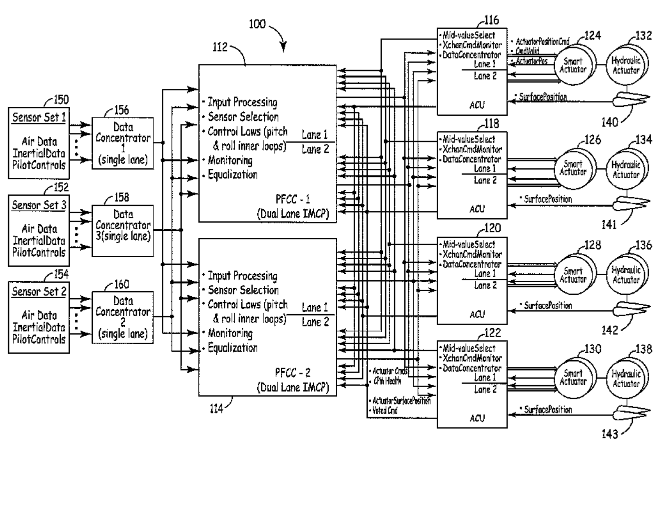
(57) **ABSTRACT**

A monitoring system and methods are provided for a distributed and recoverable digital control system. The monitoring system generally comprises two independent monitoring planes within the control system. The first monitoring plane is internal to the computing units in the control system, and the second monitoring plane is external to the computing units. The internal first monitoring plane includes two in-line monitors. The first internal monitor is a self-checking, lock-step-processing monitor with integrated rapid recovery capability. The second internal monitor includes one or more reasonableness monitors, which compare actual effector position with commanded effector position. The external second monitor plane includes two monitors. The first external monitor includes a pre-recovery computing monitor, and the second external monitor includes a post recovery computing monitor. Various methods for implementing the monitoring functions are also disclosed.

18 Claims, 7 Drawing Sheets



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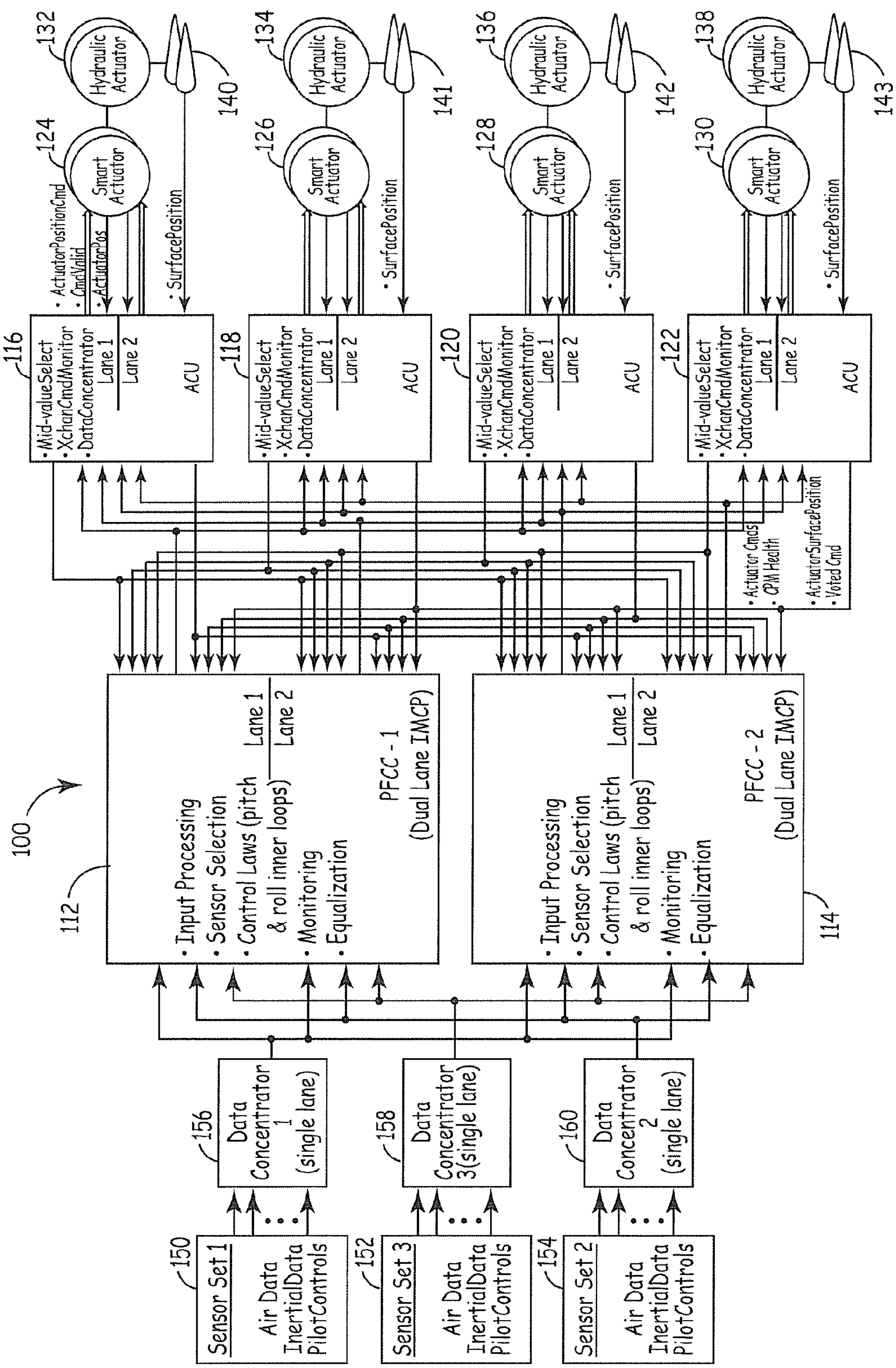
100
112
114
PFCC - 1
(Dual Lane IMCP)
PFCC - 2
(Dual Lane IMCP)
• Input Processing
• Sensor Selection
• Control Laws (pitch & roll inner loops)
• Monitoring
• Equalization
Lane 1
Lane 2
116
118
120
122
• Mid-valueSelect
• XchanCmdMonitor
• DataConcentrator
ACU
124
126
128
130
Smart Actuator
132
134
136
138
Hydraulic Actuator
140
141
142
143
• ActuatorPositionCmd
• CmdValid
• ActuatorPos
• SurfacePosition
• Actuator Cmds
• CPM Health
• ActuatorSurfacePosition
• Voted Cmd
156
158
160
Data Concentrator 1 (single lane)
Data Concentrator 3(single lane)
Data Concentrator 2 (single lane)
150
152
154
Sensor Set 1
Sensor Set 3
Sensor Set 2
Air Data
InertialData
PilotControls

FIG. 1

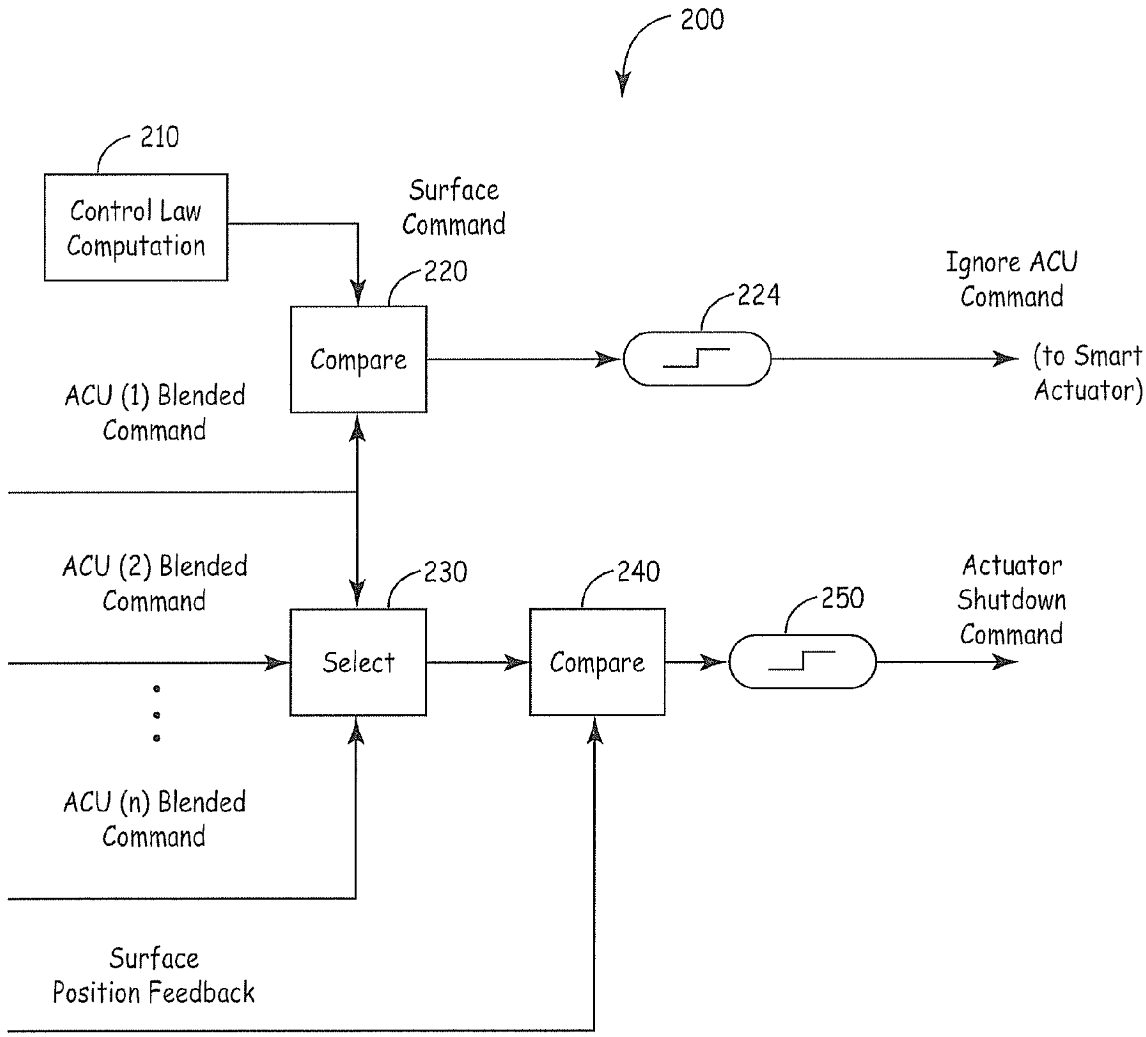
200
210
Control Law Computation
Surface Command
220
Compare
224
Ignore ACU Command
(to Smart Actuator)
ACU (1) Blended Command
ACU (2) Blended Command
230
Select
240
Compare
250
Actuator Shutdown Command
ACU (n) Blended Command
Surface Position Feedback

FIG. 2

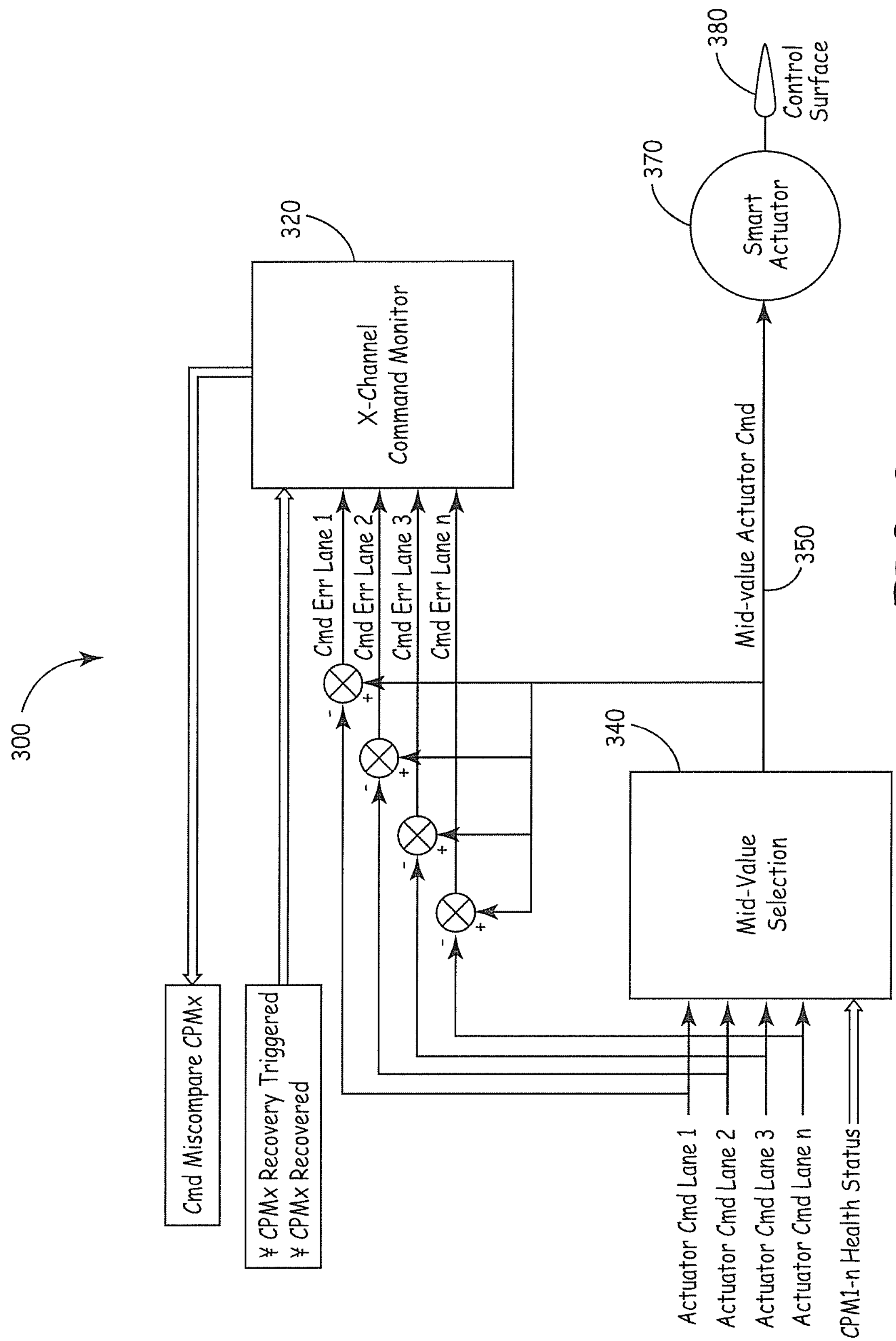
300
Cmd Miscompare CPMx
¥ CPMx Recovery Triggered
¥ CPMx Recovered
X-Channel Command Monitor
320
Cmd Err Lane 1
Cmd Err Lane 2
Cmd Err Lane 3
Cmd Err Lane n
Mid-Value Selection
340
Mid-value Actuator Cmd
350
Smart Actuator
370
Control Surface
380
Actuator Cmd Lane 1
Actuator Cmd Lane 2
Actuator Cmd Lane 3
Actuator Cmd Lane n
CPM1-n Health Status

FIG. 3

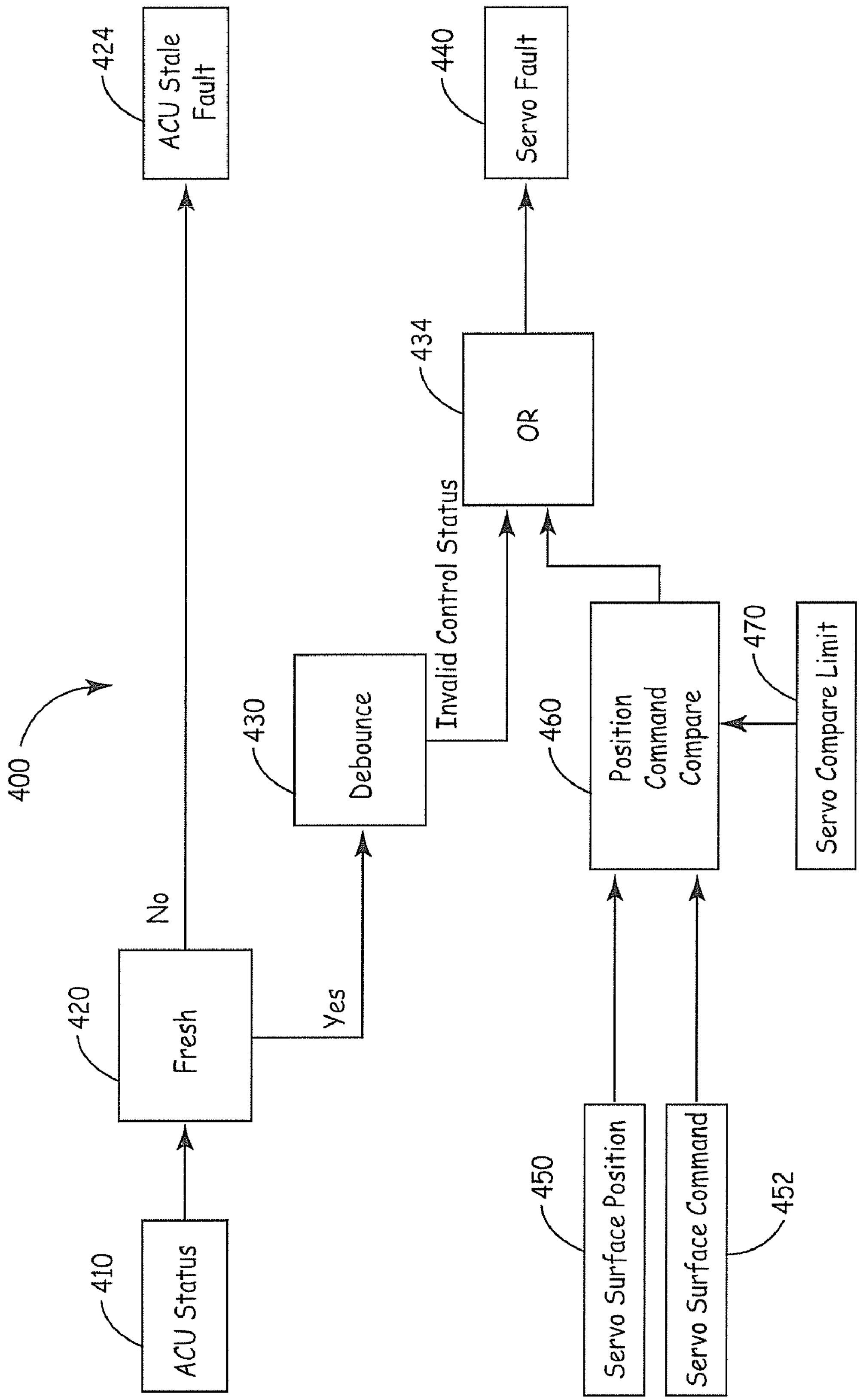
400
410
ACU Status
420
Fresh
No
Yes
424
ACU Stale Fault
430
Debounce
Invalid Control Status
434
OR
440
Servo Fault
450
Servo Surface Position
452
Servo Surface Command
460
Position Command Compare
470
Servo Compare Limit

FIG. 4

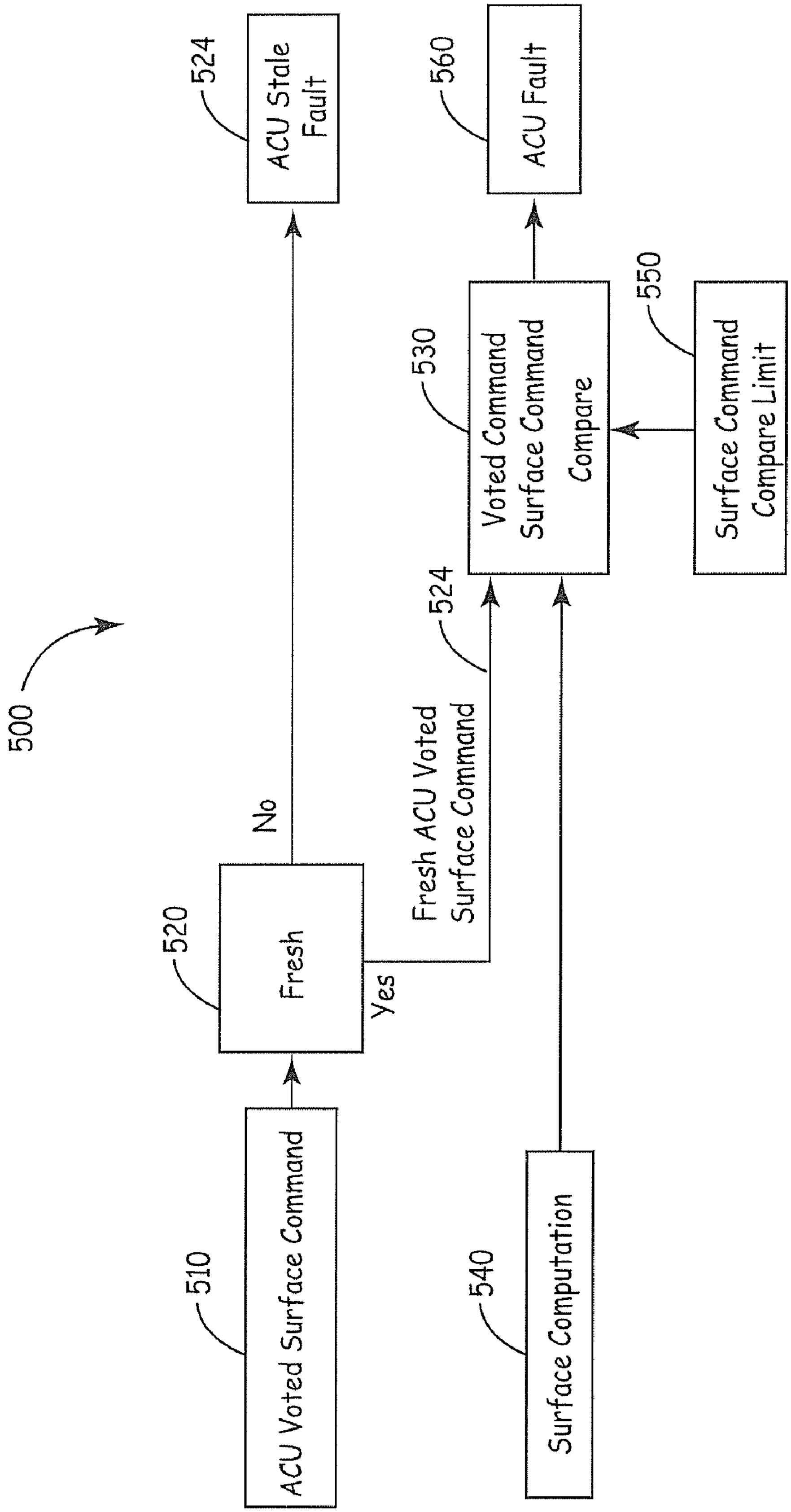
500
510
ACU Voted Surface Command
520
Fresh
Yes
No
524
ACU Stale Fault
Fresh ACU Voted Surface Command
524
530
Voted Command Surface Command Compare
540
Surface Computation
550
Surface Command Compare Limit
560
ACU Fault

FIG. 5

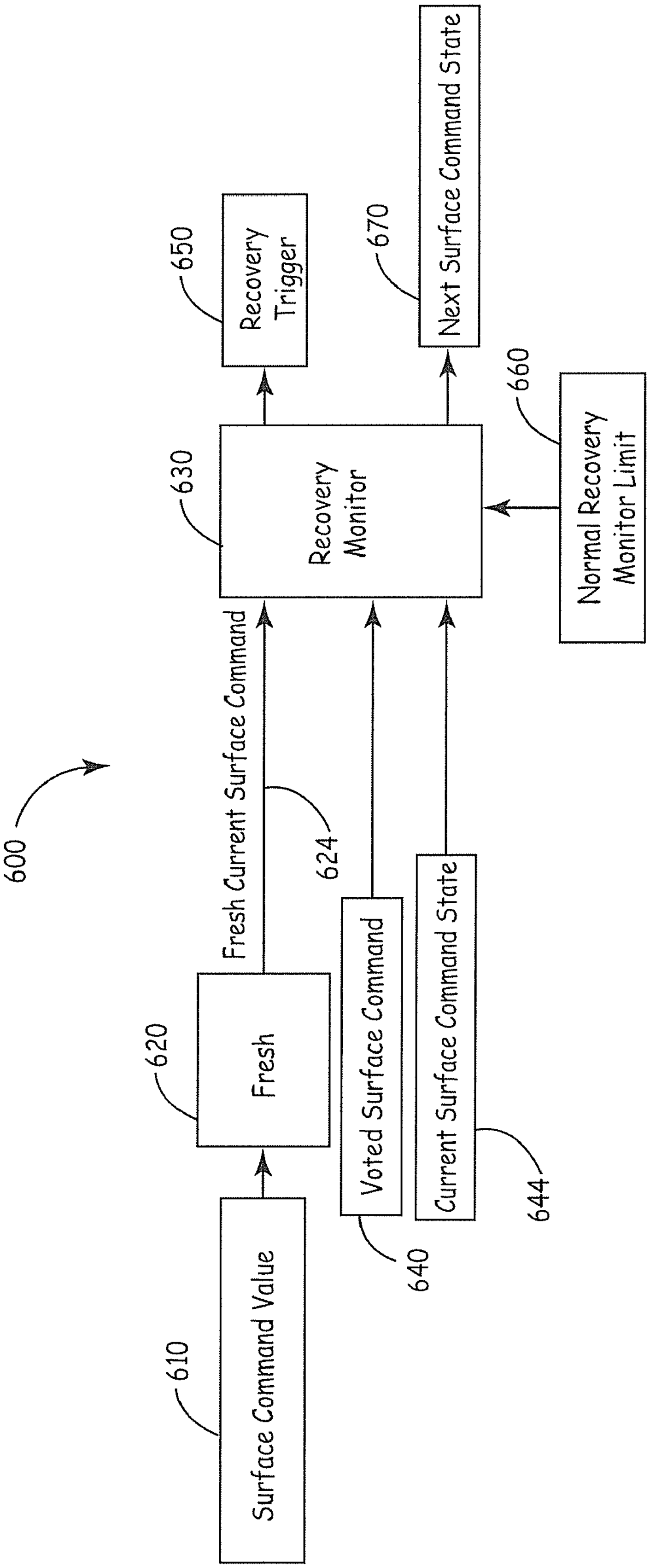
600
610
Surface Command Value
620
Fresh
Fresh Current Surface Command
624
640
Voted Surface Command
644
Current Surface Command State
630
Recovery Monitor
650
Recovery Trigger
670
Next Surface Command State
660
Normal Recovery Monitor Limit

FIG. 6

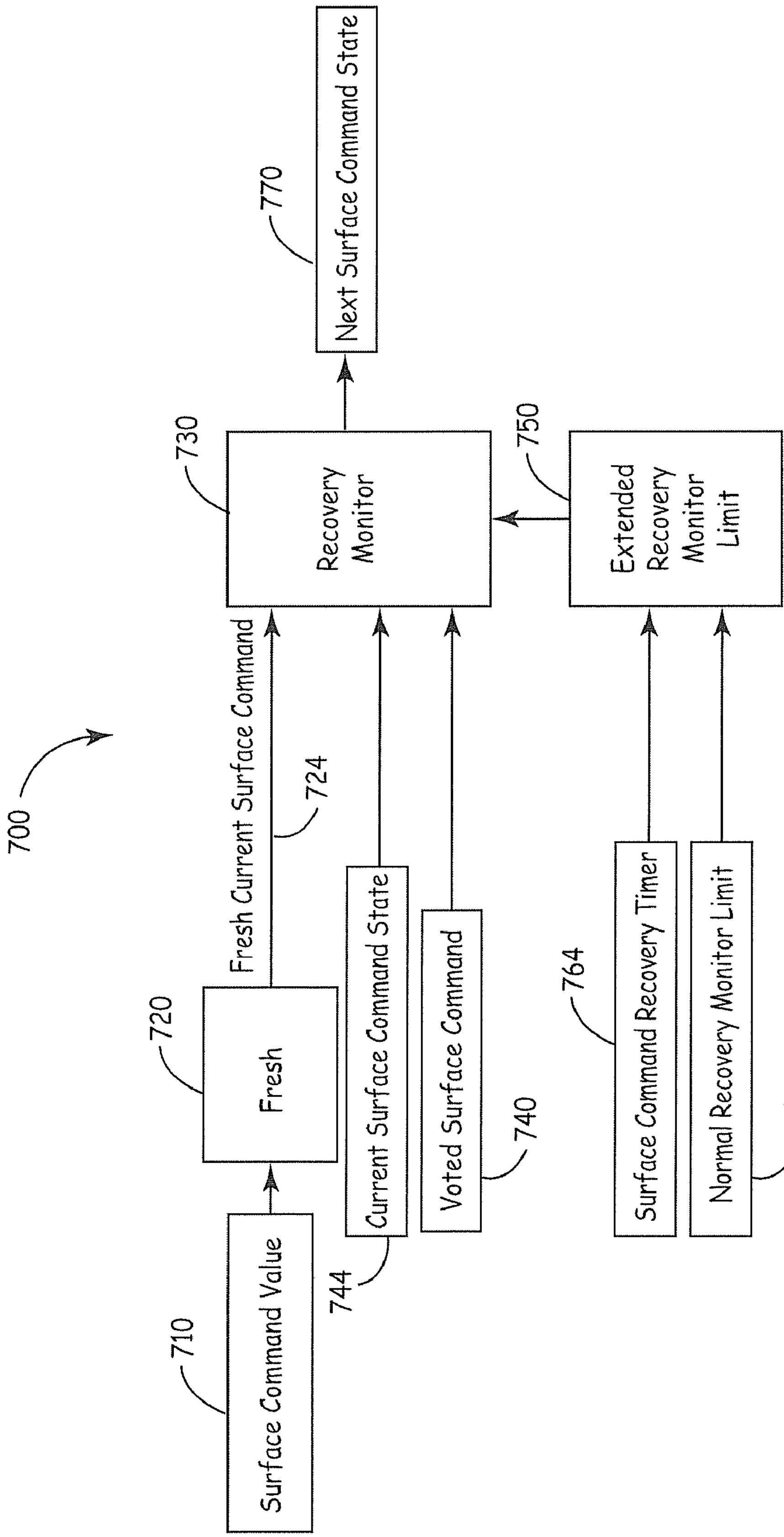
700
Surface Command Value
710
Fresh
720
Fresh Current Surface Command
724
Current Surface Command State
744
Voted Surface Command
740
Recovery Monitor
730
Extended Recovery Monitor Limit
750
Surface Command Recovery Timer
764
Normal Recovery Monitor Limit
760
Next Surface Command State
770

FIG. 7

MONITORING SYSTEM AND METHODS FOR A DISTRIBUTED AND RECOVERABLE DIGITAL CONTROL SYSTEM

This application claims the benefit of priority to U.S. Provisional Application No. 60/705,843, filed on Aug. 5, 2005, which is incorporated herein by reference. The present application is related to U.S. patent application Ser. No. 11/381,608, filed May 4, 2006, and to U.S. patent application Ser. No. 11/381,652, filed May 4, 2006, both of which are incorporated herein by reference.

The U.S. Government may have certain rights in the present invention as provided for by the terms of Contract No. CRA NCC-1-393 with NASA.

BACKGROUND TECHNOLOGY

Computers have been used in digital control systems in a variety of applications, such as in industrial, aerospace, medical, scientific research, and other fields. In such control systems, it is important to maintain the integrity of the data produced by a computer. In conventional control systems, a computing unit for a plant is typically designed such that the resulting closed loop system exhibits stability, low-frequency command tracking, low-frequency disturbance rejection, and high-frequency noise attenuation. The "plant" can be any object, process, or other parameter capable of being controlled, such as an aircraft, spacecraft, medical equipment, electrical power generation, industrial automation, valve, boiler, actuator, or other device. A control effector is used to provoke a response by the plant. For example, when the plant is an aircraft, control effectors may be in the form of flight control surfaces such as rudders, ailerons, and/or elevators.

Various types of failures or faults may be encountered by conventional computing units found in control systems. A "hard fault" is a fault condition typically caused by a permanent failure of the analog or digital circuitry. For digital circuitry, a "soft fault" is typically caused by transient phenomena that may affect some digital circuit computing elements resulting in computation disruption, but does not permanently damage or alter the subsequent operation of the circuitry.

Soft faults may be caused by electromagnetic fields created by high-frequency signals propagating through the computing system. Soft faults may also result from spurious intense electromagnetic signals, such as those caused by lightning that induce electrical transients on system lines and data buses which propagate to internal digital circuitry setting latches into erroneous states. In addition to lightning, other elements of the electromagnetic environment (EME) such as high-intensity radiated fields (HIRF), radio communications, radar pulses, and the intense fields associated with electromagnetic pulses (EMP) may also cause soft faults. Further, high-energy atomic particles from a variety of sources (e.g., atmospheric neutrons, cosmic radiation, weapon detonation, etc.) may deposit sufficient energy in the bulk semiconductor material of a digital device to set electronic circuits into erroneous states. With the advent of smaller integrated circuits running at high speeds, soft faults are becoming more common such as in the radiation environment encountered by aircraft traveling at high altitudes. In such an environment, computing circuits containing state-of-the-art digital devices may be more susceptible to failure.

In conventional control systems, various forms of redundancy have been used in an attempt to reduce the effects of faults in critical systems. Multiple processing units, for example, may be used within a computing system. In a system with three processing units, for example, if one processor is

determined to be experiencing a fault, that processor may be isolated and/or shut down. The fault may be corrected by correct data (such as the current values of various control state variables) being transmitted (or "transfused") from the remaining processors to the isolated unit. If the faults in the isolated unit are corrected, the processing unit may be re-introduced to the computing system along with the other two processing units.

Dissimilar computational redundancy is used to prevent the introduction of generic faults in control system architectures. Generic faults refer to common errors in system redundancies. Such errors can occur in the design and development of the hardware and software elements within general purpose computers that are used in control system architectures. As such, dissimilar computational redundancy would entail each redundant hardware element using a dissimilar microprocessor and each redundant microprocessor executing software (e.g., operating system, application, etc.) that was developed using a different programming language.

Other methods that have been used to help ensure the continued operation of control systems include the use of dissimilar technology, distributed computation redundancy, equalization, and mid-value voting. Each of these methods, however, generally requires at least one processing unit to remain operational at all times to preserve state variables. While the control systems may remain operational if all but one of the processing units experience a soft fault and the correctly-operating unit can be identified, the control system will not operate properly if all of the processors simultaneously experience soft faults. Similarly, if a lone properly-operating unit cannot be identified within the system, the system will not recover, as there would be no identifiable operating unit with correct values for all of the state variables to be transfused to the remaining units. In addition, because of the transfusion of state variables from other processing units, the system recovery may be relatively slow. It may therefore take an extended period of time for all processing units within the system to resume normal operation. In the meantime, redundant control is undesirably lost or degraded.

In the aerospace field, digital flight control systems are frequently interposed between the pilot and the flight control surfaces of an aircraft. Such systems may include fly-by-wire, auto-pilot, and auto-land systems. In a fly-by-wire system, in lieu of pilot controls being mechanically coupled (e.g., via cables or hydraulics) to the various primary flight control surfaces of the aircraft (such as the ailerons, elevators, and rudder), the position and movements of a pilot's controls are electronically read by sensors and transmitted to a computing system. The computing system typically sends electronic control signals to actuators of various types that are coupled to the primary flight control surfaces of the aircraft. The actuators are typically configured to move one or more control surfaces according to inputs provided by the pilot, or in response to feedback measured by a sensor on the aircraft. Failure of the control system could thus have catastrophic effects on the aircraft. Similarly, industrial, medical, or other systems may be gravely affected by certain control system failures.

In conventional flight control system (FCS) architectures, recovery from soft faults of FCS architectural elements, particularly in the flight control computer, is either not possible, has to resort to recovery attempts after a grace period of time, or requires recycling of power such as rebooting the computer. Any of these circumstances can impact the mean time between unscheduled removals (MTBUR) negatively. In addition, tight tolerance monitoring has been dependant on synchronous operations for tight tracking of redundant elements, and has been relatively federated and not easily scaleable.

High integrity digital flight control systems usually require incorporation of redundant elements to achieve required reliability. Management of systems to provide maximum theoretically possible availability of the redundant elements in the presence of soft faults is difficult to achieve without requiring close synchronization of the computing elements or other technically difficult monitoring mechanisms.

BRIEF DESCRIPTION OF THE DRAWINGS

Features of the present invention will become apparent to those skilled in the art from the following description with reference to the drawings. Understanding that the drawings depict only typical embodiments of the invention and are not therefore to be considered limiting in scope, the invention will be described with additional specificity aid detail through the use of the accompanying drawings, in which:

FIG. **1** is a schematic depiction of a digital control system that can employ the monitoring features of the invention according to one embodiment;

FIG. **2** is a schematic depiction of a time magnitude monitor that can be used in a digital control system;

FIG. **3** is a block diagram of an exemplary actuator command selection and lane command monitor employing rapidly recoverable computing elements;

FIG. **4** is a block diagram of a servo monitor that can be used in a digital control system;

FIG. **5** is a block diagram of an actuator control unit monitor that can be used in a digital control system;

FIG. **6** is a block diagram of an actuator control unit computing monitor that can be used in a digital control system; and

FIG. **7** is a block diagram of a post recovery computing monitor that can be used in a digital control system.

DETAILED DESCRIPTION

The present invention relates to a monitoring system and methods for a distributed and recoverable digital control system. The monitoring system generally comprises two independent monitoring planes within the control system. The first monitoring plane is internal to the computing units in the control system. The second monitoring plane is external to the computing units in the control system.

The internal first monitoring plane includes two in-line monitors. The first monitor is a self-checking, lock-step-processing monitor with integrated rapid recovery capability. The second monitor includes one or more reasonableness monitors, which compare actual effector position with commanded effector position.

The external second monitoring plane includes two monitors. The first monitor includes a pre-recovery computing monitor, and the second monitor includes a post recovery computing monitor. Once the computational elements have been deemed to be computing errant outputs, a rapid recovery is triggered. The monitoring of that errant computational element then follows a post recovery algorithm to determine if the recovery was successful. If the recovery was successful the outputs of the recovered element are re-enabled to be blended with the remaining system outputs in computing the blended system output. If the recovery was not successful the recovered computational element is eliminated from the output blending function computation until the system is restarted.

Further details related to the monitoring system and techniques of the invention are described hereafter.

In the following description, various embodiments of the present invention may be described herein in terms of various architecture elements and processing steps. It should be appreciated that such elements may be realized by any number of hardware or structural components configured to perform specified operations. For purposes of illustration only, exemplary embodiments of the present invention will frequently be described herein in connection with aircraft avionics. The invention is not so limited, however, and the concepts and devices disclosed herein may be used in any control environment. Further, it should be noted that although various components may be coupled or connected to other components within exemplary system architectures, such connections and couplings can be realized by direct connection between components, or by connection through other components and devices located therebetween. The following detailed description is, therefore, not to be taken in a limiting sense.

According to various exemplary embodiments of the invention, a control system architecture suitably includes sufficient computation redundancy and control command management to either isolate or recover a faulted processor, or to recover all processing units of the redundant system without adverse effects. Computational redundancy may be provided with multiple processors or processing units within a computer or computing platform. In addition to isolating and recovering from internal faults, various embodiments allow processing units to detect faults in other system elements such as sensors, adaptors, actuators and/or effectors. Further embodiments may also include one or more actuator adaptor units, that through the detection of adverse data errors, detect faults in other system components (that are in addition to the processing units) and issue discrete instructions to trigger a recovery.

An exemplary control system architecture suitably includes multiple processors, each of which is configured for rapid recovery from various faults. The term "rapid recovery" indicates that recovery may occur in a very short amount of time. To maintain the operation of a control system, it is generally desirable that a recovery from a soft fault takes place within about 1 to 2 computing frames. As used herein, a "computing frame" is the time needed for a particular processing unit to perform a repetitive task of a computation, e.g., the tasks that need to be calculated continuously to maintain the operation of the controlled plant. In some embodiments, processor recovery is performed within about 1 computing frame and redundancy recovery is performed within about 1 or 2 computing frames, or otherwise in a short enough time period so as to have only minimal effects, if any, on system performance.

The ability of a processor to initiate recovery from a soft fault allows various embodiments of the present invention to aid in the recovery of the system as a whole. In addition, soft faults may be detected in the same computing frame or within several frames in which the faults occur. In embodiments where faults are detected within a single computing frame each processor need only store control and logic state variable data for the immediately preceding frame for use in recovery purposes, which may take place essentially instantaneously. Accordingly, the dependence of each component upon other redundant components is suitably reduced.

Instructions for carrying out the various methods, process tasks, calculations, control functions, and the generation of signals and other data used in the operation of the system of the invention are implemented, in some embodiments, in software programs, firmware, or computer readable instructions. These instructions are typically stored on any appropriate computer readable medium used for storage of computer readable instructions or data structures. Such computer readable media can be any available media that can be accessed by a general purpose or special purpose computer or processor, or any programmable logic device.

By way of example, and not limitation, such computer readable media can include floppy disks, hard disks, ROM, flash memory ROM, nonvolatile ROM, EEPROM, RAM, CD-ROM, DVD-ROM, or other optical disk storage, magnetic disk storage, or other magnetic storage devices, or any other medium that can be used to carry or store desired program code means in the form of computer executable instructions or data structures. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a computer, the computer properly views the connection as a computer readable medium. Thus, any such connection is properly termed a computer readable medium. Combinations of the above are also included within the scope of computer readable media. Computer executable instructions comprise, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing device to perform a certain function or group of functions.

The system of the invention will also be described in the general context of computer readable instructions, such as program modules, being executed by a processor. Generally, program modules include routines, programs, objects, data components, data structures, algorithms, etc. that perform particular tasks or implement particular abstract data types. Computer executable instructions, associated data structures, and program modules represent examples of a program code means for executing steps of the methods disclosed herein. The particular sequence of such executable instructions or associated data structures represents examples of corresponding acts for implementing the functions described in such steps.

Referring now to FIG. **1**, an exemplary scaleable architecture of a digital control system **100** that can employ the monitoring system and method of the invention includes a first computing unit **112** and a second computing unit **114**. The computing units **112** and **114** can be any digital control device such as a digital computer or processor, and provide for redundancy in processing. Each computing unit **112**, **114** suitably includes one or more processing devices capable of executing multiple and/or simultaneous software processes. As shown, the computing units **112** and **114** can include real-time multi-tasking computing platforms such as a primary flight control computer (PFCC). The PFCC can be an integrated modular computing platform (IMCP) with dual computational lanes.

The computing units **112** and **114** provide input processing, sensor selection, control laws (e.g., pitch, yaw, and roll inner loops), monitoring (e.g., actuator and surface position monitoring), equalization, rapid recovery, redundancy management, and any appropriate recovery triggers. Although control system **100** is shown with two computing units, additional computing units can be employed if desired.

Each of the computing units **112** and **114** are in operative communication with a multitude of actuator control units (ACUs) **116**, **118**, **120**, and **122**, which provide for actuator command (Cmd) management and have dual computing lanes. The ACUs perform command blending and selection, and use other redundant actuator command values while a computing platform such as a PFCC lane is recovering. The ACUs also perform monitoring of actuator command lanes, data concentration, and initiation of a selective and isolated recovery trigger of each monitored application. The ACUs can also be redundant per control axis. Although control system **100** is shown with four ACUs, a varying number of ACUs can be employed depending upon system requirements. For example, in some embodiments three or more ACUs can be employed in a control system according to the invention.

Each ACU **116**, **118**, **120**, and **122** can be in operative communication with a respective one of a smart actuator **124**, **126**, **128**, and **130**. An actuator is made "smart" when an electronics module such as an electronic interface unit (EIU) is added to the basic actuator. The smart actuators used in the control system can be dual-channel, fail-passive, electromechanical actuators, which contain two independent computational lanes. The smart actuators receive actuator position command signals from the ACUs. The smart actuators also determine validity of commands from the computing unit based on command validity flags and activity monitoring. The smart actuators **124**, **126**, **128**, and **130** are configured to provide feedback to the respective ACU **116**, **118**, **120**, and **122** related to actuator position information.

The smart actuators **124**, **126**, **128**, and **130** can optionally be in operative communication with a respective servo or actuator device such as hydraulic actuators **132**, **134**, **136**, and **138**. The hydraulic actuators **132**, **134**, **136**, and **138** can be respectively coupled to various control effectors **140**, **141**, **142**, and **143** such as, for example, various primary flight control surfaces of an aircraft (e.g., rudders, ailerons, and/or elevators). The control effectors **140-143** are configured to provide feedback to the respective ACU **116**, **118**, **120**, and **122** related to surface position information.

As depicted in FIG. **1**, the computing units **112** and **114** receive data inputs from sensor sets **150**, **152**, and **154**, which can include air data, inertial data, or commands from an operator (e.g., pilot controls, etc.). The sensor sets can include any number of gyroscopes, vehicle position sensors, airflow sensors, temperature sensors, and/or other sensing devices as may be appropriate for the particular implementation. A data concentrator **156**, **158**, and **160** with a single lane can be implemented between each sensor set **150**, **152**, **154** and computing units **112** and **114**. The data concentrators suitably receive and concentrate data from the sensors to provide an interface to computing units **112** and **114** as appropriate. The data concentrators may also provide sensor validity monitoring to ensure that the sensors remain active. Each of the sensors may optionally include rapid recovery elements if available and desired for the particular implementation.

The control system **100** can be suitably implemented, for example, as part of a digital flight control system to provide functions for the safe flight and landing of aerospace vehicles. The control system **100** provides for independent recovery of any computing lane, and all system elements can be executed asynchronously. Also, control system **100** can accommodate the asynchronous operation of dissimilar computational redundancy. For example, the PFCC performs equalization of surface positions by bringing diverging data back to the same value or close to the same value. An actuator command management voting algorithm accommodates asynchronous surface command inputs such that the PFCC, ACU, and other elements can execute asynchronously, and can accommodate computational lanes using dissimilar computational redundancy.

The computing platform such as the PFCC provides a real-time multi-tasking computer system with rollback recovery capability. The PFCC enables integration of functions, and applications may selectively use the recovery function as required. The recovery mechanism operation can be verifiable using common built-in-test methods, which can be used to verify operation of the recovery mechanism at any time. The PFCC can also provide monitoring of ACU surface commands and surface positions.

During operation of control system **100**, computing units **112**, **114** receive input from sensor sets **150**, **152**, **154** via data concentrators **156**, **158**, **160**. Each computing unit provides the appropriate data to each computational lane thereof, which operate as separate partitioned processing units. Accordingly, each data set from redundant sensor and command data sets can be simultaneously processed in multiple isolated processing units. The commands signals from each lane of computing units **112**, **114** propagate to each of the ACUs **116**, **118**, **120**, and **122**. The ACUs transmit the command signals to the smart actuators **124**, **126**, **128**, and **130**, which then perform the requested commands as appropriate to control the hydraulic actuators **132**, **134**, **136**, **138**, and thereby the control effectors **140-143**. During normal operation, the output signals from each processing unit can be monitored internally, or externally by the ACUs, to ensure that each of the computing units **112**, **114** are producing results within a predetermined tolerance of the remaining computing units.

Each processing unit of computing units **112**, **114** is configured to be capable of rapid recovery from soft faults. To accomplish rapid recovery, each processing unit is configured to retrieve control and logic state variable data from internal memory locations such as a high integrity random access memory. Using the retrieved state variables and appropriate sensor data, each processing unit can fully recover from a soft fault relatively quickly without requiring a data transfusion from another computing unit. The rapid recovery cycle involves halting processor execution, instating state variables from a protected memory area, and starting execution again at an appropriate location in the program execution cycle. Through the use of command blending, equalization, or other techniques, it is not necessary to synchronize with the remaining processing units when initiating the rapid recovery cycle.

A suitable fault recovery system that can be used in the control system of the present invention is disclosed in copending U.S. patent application Ser. No. 11/058,764 filed on Feb. 16, 2005, which is incorporated herein by reference.

During a rapid recovery cycle, the tolerance used in an ACU to determine if a processing unit is operating properly may be relaxed for that particular processing unit. For example, during normal operation, there may be a predetermined tolerance, within which each of the processing units is expected to operate. If a processing unit produces values that are not within the predetermined tolerance, that processing unit may be determined to be suffering from a soft fault, and a rapid recovery cycle may be initiated. During the rapid recovery cycle, the predetermined tolerance for the affected processing unit may be initially widened and then narrowed over a predetermined time period such that further deviations are acceptable until the processing unit resumes normal operation.

Furthermore, the output of the processing unit may not be included in the derivation of the output from the ACU (e.g., computation of the mid-value) until the output comes within the relaxed tolerance. If the output comes within tolerance (indicating that the computing unit has stabilized) within a predetermined period of time, it may once again be included in the output derivation. Before the predetermined time has expired and the processing unit output has come within tolerance, requests for placing the processing unit into a rapid recovery state may be suspended or "masked" to allow the processing unit to recover. Once the processing unit has stabilized from the recovery cycle, it may be subjected to the previous tolerances. If the output does not come within tolerance within the predetermined time, another request to place the processing unit into a rapid recovery state may be issued.

In general, if the output of a recovered element falls outside of the relaxed tolerance following recovery, that computational element is kept off-line until the system is restarted (i.e., re-powered). Such a failure indicates that the recovery was unsuccessful. While rare, this provides a means for excluding a computational element that does not return to the tolerance within a specified time period. The tolerance used following recovery is tightened over a specific time period until it reaches the original tolerance.

One technique for computing the blended control output involves computing a "mid-value" in which the signals from a processing unit are used to compute a mean and/or median of all of the values produced. This mid-valve is then compared to each signal from each of the processing units in the system. If a discrepancy exists between any particular value produced by any lane and the mean and/or median of all the values (i.e., the mid-values), an error condition is detected to exist the appropriate processing unit initiates a rapid recovery cycle. The discrepancy from the mid-values may be based upon any tolerance value, which can in turn be adjusted based upon desired conditions. The detection of discrepancy from a mean or median value can be processed very rapidly, thus potentially resulting in an identification of an error within one or two computational frames of the value being produced. Accordingly, differences from mid-values may be computed based upon previous mid-values (i.e., values maintained from a previous frame), or can be computed in real time as appropriate.

Alternatively, when one or more of the ACUs **116**, **118**, **120**, **122** sense that one of the computing units **112**, **114** are not supplying signals that lie within certain tolerances, the ACUs may transmit a signal to the computing unit in question to request the start of a rapid recovery cycle for a particular processing unit. The computing units of the control system are configured to perform redundancy management actions such as equalization, in which the control signal generated by each processing unit is driven toward fine adjustments in the computed mid-value, so that the signals produced by each processing unit result in an equalized control command. Such implementations typically do not require tight synchronization between the various processing units to achieve "equalized" command values because each command signal is driven toward the other signals (i.e., toward a mid-value).

An equalization signal is derived from feedback of control effector positions and is used to cancel out drift in the surface commands, preventing divergence of computed surface commands. This allows tight monitoring and comparison of the command signals in the ACU and the rapid detection of computing element errors in time to command recovery before state variable values are permanently lost.

Use of the equalization method allows asynchronism of the control computation elements so that the implementation of the elements may be either similar or dissimilar as called for in order to meet reliability and availability requirements. For example, different types of processors may be employed in the computing units if desired. The equalization scheme also accommodates errant surface positions

By implementing mid-value signal selection and equalization, rapid recovery of redundant elements is provided for in a transparent, seamless way. That is, any data errors in any processing unit do not propagate through the system to adversely affect the control function. If one processing unit encounters a soft fault and proceeds to a recovery cycle, the remaining operating processing units are unaffected by the recovery cycle and the operation of the control system as a whole is unaffected. Because the error is very quickly confined, recovery of redundant control commands can be processed very rapidly.

As discussed previously, the monitoring system of the invention generally comprises two independent monitoring planes within a control system. The first monitoring plane is internal to the computing units in the control system. For example, the first monitoring plane can be implemented in computing units **112**, **114** of control system **100**. The second monitoring plane is external to the computing units in the control system, and can be implemented in the ACUs of control system **100**.

The internal first monitoring plane includes two in-line monitors. The first internal monitor is a self-checking, lockstep-processing platform with integrated rapid recovery capability. The first monitor triggers a recovery mechanism on a lane miscompare or a lockstep fault, and may be readily integrated with existing state of the art monitoring methods implemented in either hardware or software (e.g., error detection and correction (EDC) codes, parity, and others).

The second internal monitor of the first monitoring plane includes reasonableness monitors, which compare actual surface positions with commanded surface positions. Such monitors can include time magnitude monitoring; servo monitoring in which a servo monitor compares effector commands with effector positions and isolates faults to actuator/servo devices; and ACU monitoring, in which an ACU monitor compares effector command computations by a computer with ACU blended effector commands, and isolates faults to an ACU. A built-in test of recovery mechanism can also be provided, in which a simulated soft fault triggers a recovery mechanism, followed by the test recovery memory contents being compared to known test values. This verifies that the recovery mechanism is fully operational.

FIG. **2** is a block diagram of an exemplary time magnitude monitor **200** that can be used in a reasonableness monitor. During operation of monitor **200**, a processing unit of the control system performs a control law computation **210** and sends a computed surface command to a compare module **220** for comparison with an ACU(**1**) blended command. A smart actuator is commanded to ignore the ACU(**1**) blended command when deviations between the ACU(**1**) blended command output and the computed surface command are beyond an established limit for a specified time **224**. The ACU blended actuator commands for ACU(**1**), ACU(**2**) . . . ACU(n) are sent to a select module **230**, and the selected command is sent to a compare module **240** for comparison with a surface position feedback signal. When deviations between the selected command output and the surface position feedback signal exceed an established limit for a specified time **250**, the actuator is commanded to shutdown.

FIG. **4** depicts an exemplary servo monitor **400** that can be used in a reasonableness monitor to isolate faults to either a servo/actuator or an ACU. This monitor is not limited to monitoring ACUs or surface servos/actuators, but can apply to a variety of control system implementations. During operation of monitor **400**, each computing unit such as an FCC monitors each servo input for each control axis. In a first monitoring lane, an ACU status value **410** is sent to a fresh test module **420** to determine its freshness. If the ACU status value is not fresh, it is flagged as an ACU stale fault **424** and is excluded from further monitoring. A fresh ACU status value is sent to a debounce module **430** for validation. An invalid control status value is sent to an OR logic module **434**, resulting in a servo fault **440** being reported. In a second monitoring lane, a servo surface position **450** and a servo surface command **452** are sent to a position/command compare module **460** for comparison. If the servo surface position **450** and servo surface command **452** have a difference that exceeds a predetermined servo compare limit **470**, a signal is sent to OR logic module **434**, resulting in a servo fault **440** being reported.

FIG. **5** illustrates an exemplary ACU monitor **500** that can be used in a reasonableness monitor. The monitor **500** performs monitoring of computing elements in a pre-recovery trigger mode, with variable tolerance not being applied at this point. During operation of monitor **500**, each ACU input in each control axis is monitored by each computing unit such as an FCC. An ACU voted surface command **510** is sent to a fresh test module **520** to determine its freshness. If the ACU voted surface command is not fresh, it is flagged as ail ACU stale fault **524** and is excluded from further monitoring. A fresh ACU voted surface command **524** is sent to a voted command/surface command compare module **530** for comparison with a surface computation **540**. If the difference between ACU voted surface command **524** and surface computation **540** exceeds a predetermined surface command compare limit **550**, an ACU fault **560** is asserted.

As discussed previously, the external second monitoring plane includes two monitors on ACUs. The first external monitor includes a pre-recovery computing monitor, and the second external monitor includes a post recovery computing monitor.

In the pre-recovery computing monitor, multiple command computations are independently monitored across multiple redundant computing units. Fresh and valid commands are combined to form a blended command. Each input is compared with the blended command and a rapid recovery of errant computational elements is triggered within a computing unit when the difference between the blended command and a command computation is outside a predetermined monitor window limit. A computational element that is commanded to recover is excluded from pre-recovery monitoring until it is restored.

FIG. **3** shows an exemplary actuator command selection and x-lane command monitor **300** that can be used in the pre-recovery computing monitor. The monitor **300** includes a command error monitor **320** and a mid-value selection module **340**. During operation of monitor **300**, actuator command values are received by mid-value selection module **340** from actuator command lanes 1, 2, 3, . . . n, which also send the command values to command error lanes 1, 2, 3, . . . n that communicate with command monitor **320**. The mid-value selection module **340** includes temporary or permanent deselection of an actuator command lane based on CPM recovery (health) status/history. A selected mid-value actuator command **350** is sent to a smart actuator **370** that operatively communicates with a control surface **380**. The selected mid-value command **350** is also sent to command error lanes 1, 2, 3 . . . n for command monitoring by monitor **320**. The command error monitor **320** is initially widened for a specific CPM following a recovery trigger and narrows over a specific time window until the tolerance reaches the pre-recovery value. The command monitor also flags a command miscompare to a CPM when an error is detected. The logic of monitor **300** can be replicated for each control surface.

FIG. **6** depicts an exemplary ACU pre-recovery monitor **600** that can be used in the pre-recovery computing monitor. During operation, a surface command value **610** is sent to a fresh test module **620** to determine its freshness. A fresh current surface command **624** is sent to a recovery monitor **630** and compared with an ACU voted surface command **640** and a current surface command state **644**. A recovery trigger **650** is generated if the difference between current surface command **624**, voted surface command **640**, and current surface command state **644** exceeds a normal recovery monitor limit **660**. Thereafter, a next surface command state **670** is set to recovery. The computer elements that are commanded to recover are excluded from recovery monitoring until restored. When the difference between a current surface command **624**, a voted surface command **640**, and current surface command state **644** remains within the normal recovery monitor limit **660**, a next surface command state **670** remains in a normal state and no recovery trigger is generated.

The post recovery computing monitor in the second external monitoring platform monitors the integrity of a previously recovered computational element that has been gracefully restored within a redundant control unit. After recovery, the recovered computational element is monitored using a variable time magnitude monitor, in which a recovery monitor window is extended or widened for recovering computer surface command inputs following an external recovery trigger. The recovery monitor window narrows with time until it reaches the initial surface command monitor window limit. This allows a recovered computational element to gracefully return to a viable state (fresh and reasonable) in a mid-value computation. An input value from the recovered computational element is restored to a viable state and included in the mid-value vote if the difference between the input value and the mid-value remains within the widened monitoring window for the allocated recovery time. If the input value from the recovered computational element falls outside the widened monitor window, the input value is discarded until a system restart or power cycle.

For example, FIG. **7** illustrates a post recovery computing monitor **700**. During operation, each ACU monitors each computer surface command value in an ACU axis. A surface command value **710** is sent to a fresh test module **720** to determine its freshness. A fresh current surface command **724** is sent to a recovery monitor **730** and compared with an ACU voted surface command **740** and a current surface command state **744**. The surface command values in the recover state, as indicated by current surface command state **744** are monitored by recovery monitor **730**. An extended recovery monitor limit **750** is determined by adding an offset to the normal recovery monitor limit **760**, and the offset is reduced as a surface command recovery timer **764** expires. A next surface command state **770** remains in a recover state while the difference between current surface command **724** and voted surface command **740** does not exceed the extended recovery monitor limit **750** and surface command recovery timer **764** has not expired. The next surface command state **770** is disabled if the difference between current surface command **724** and voted surface command **740** exceeds the extended recovery monitor limit **750**. The next surface command state **770** is set to normal if the difference between current surface command **724** and voted surface command **740** remains less than the extended recovery monitor limit **750** for the duration of the surface command recovery timer **764**. This allows current surface command value **724** to be reintroduced into the voted surface command computation.

The post recovery computer monitor can be invoked in an ACU to monitor a PFCC following a recovery of a PFCC triggered by the ACU. The PFCC outputs may be included in the ACU servo command computation if the outputs of the previously recovered PFCC fall within an acceptable range when compared to the voted or averaged value of the healthy PFCCs within the system. The recovered PFCC may be disabled for the duration of the mission if the post recovery commands do not fall within the acceptable range within a specified time period. The ACU either puts the recovered PFCC back into use after a recovery is triggered or excludes computations from the PFCC until the next system restart.

In general, the monitoring techniques of the invention are scalable, as there is no dependency on sorting, voting, or monitoring algorithms that would exclude a greater number of computational elements from being monitored. The monitoring techniques are also asynchronous and independent of surface command computations within a control system such as a primary flight control system. The monitoring techniques are also independent of servo and actuator redundancy management. Thus, the actuator controller is not required to be controlling the actuator for the monitoring methods to be active and functional.

The blended surface command computation, monitoring, and output to a servo/actuator occur in a single computational frame. Thus, prior inputs are not required. In addition, the recovery of a computational element is selective depending upon which computation is in error. The time magnitude monitoring method can be used to gracefully restore a previously recovered computational element to the original system configuration. The monitoring methods aid in computational element fault isolation to both the actuator control unit and a servo/actuator system driven by the actuator control unit.

When used in a flight control system, the present monitoring methods ensure that the pilot is always connected to control surfaces through a computer, and therefore no backup direct connection is required to ensure safe flight and landing of the aircraft. The monitoring methods allow multiple asynchronous command channels to control and monitor each individual aircraft surface.

The present monitoring methods detect a single errant computation and trigger a computer recovery within a single computational frame. The monitoring methods also monitor the recovery process and will restore a redundant element if the errant element successfully recovers. The monitoring techniques work in the presence of soft faults in the control system architectural elements and improve the mean time between unscheduled removals (MTBUR), moving it toward the mean time between failure (MTBF).

The present invention may be embodied in other specific forms without departing from its essential characteristics. The described embodiments and methods are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is therefore indicated by the appended claims rather than by the foregoing description. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed is:

1. A monitoring system for a recoverable digital control system, the monitoring system comprising:

a first monitoring plane internal to one or more computing units in the control system, the first monitoring plane comprising:

a first internal monitor comprising a self-checking, lock-step-processing monitor with integrated rapid recovery capability; and

a second internal monitor comprising one or more reasonableness monitors that compare an actual effector position with a commanded effector position; and

a second monitoring plane external to the computing units, the second monitoring plane comprising:

a first external monitor comprising a pre-recovery computing monitor; and

a second external monitor comprising a post recovery computing monitor;

wherein the first external monitor is configured to independently monitor multiple effector position command computations across the computing units;

wherein the first external monitor is configured to sort fresh and valid input commands from the computing units by magnitude, and compute a blended command by averaging two sorted input commands closest to a median of all the input commands while discarding outlying input commands from the blended command computation; and

wherein the computing units provide a real-time integrated modular computing platform.

2. The monitoring system of claim **1**, wherein the one or more reasonableness monitors comprise a time magnitude monitor that is configured to compare a blended command with a computed command.

3. The monitoring system of claim **1**, wherein the one or more reasonableness monitors comprise a servo monitor that is configured to compare effector commands with effector positions, and isolate any fault to a servo or an actuator control unit.

4. The monitoring system of claim **3**, wherein the fault comprises a soft fault.

5. The monitoring system of claim **1**, wherein the one or more reasonableness monitors comprise an actuator control unit monitor that is configured to compare command computations of a computing unit with actuator control unit commands, and isolate any fault to an actuator control unit.

6. The monitoring system of claim **5**, wherein the fault comprises a soft fault.

7. The monitoring system of claim **1**, wherein the first external monitor is configured to compare each input command with the blended command and trigger a rapid recovery of an errant computational element within a computing unit when the difference between the input command and the blended command is outside of a predetermined monitor window limit.

8. The monitoring system of claim **1**, wherein the second external monitor is configured to monitor the integrity of a previously recovered computational element.

9. The monitoring system of claim **8**, wherein the second external monitor is configured for monitoring a recovered computational element using a variable time magnitude monitor and an extended monitor window limit, wherein the extended monitor window limit narrows with time.

10. The monitoring system of claim **9**, wherein the second external monitor is configured to allow the recovered computational element to return to a viable state in a blended command computation if a difference between an input command from the recovered computational element and a blended command remains within the extended monitor window limit for an allocated recovery time.

11. The monitoring system of claim **9**, wherein the second external monitor is configured to discard any input command from the recovered computational element that falls outside the extended monitor window limit until a system restart or power cycle.

12. The monitoring system of claim **1**, wherein the second monitoring plane is implemented in one or more actuator control units.

13. The monitoring system of claim **12**, wherein the one or more actuator control units are in operative communication with one or more smart actuators.

14. The monitoring system of claim **13**, wherein the one or more smart actuators are in operative communication with one or more actuator or servo devices.

15. The monitoring system of claim **14**, wherein the actuator or servo devices are each operatively connected to one or more control effectors.

16. A method for independently monitoring multiple command computations across multiple redundant computing units, the method comprising:

sorting fresh and valid effector position commands from the computing units by magnitude;

computing a blended command by averaging two sorted input commands closest to a median of all the input commands;

discarding any outlying input commands from the blended command computation;

comparing each input command from a computational element of a computing unit with the blended command; and

triggering a rapid recovery of any errant computational element when a difference between the blended command and an effector position command computation is outside a predetermined window limit.

17. The method of claim **16**, further comprising:

monitoring integrity of a previously recovered computational element by a method comprising:

monitoring the recovered computational element using a variable time magnitude monitor in which an extended monitor window narrows with time;

allowing the recovered computational element to return to a viable state in a blended command computation if a difference between an input command from the computational element and a blended command remains within the extended monitor window for an allocated recovery time; and

discarding an input command from the recovered computational element if the input command falls outside of the extended monitor window until a system restart or power cycle.

18. A method for time magnitude monitoring comprising:

comparing a blended command output with a computed effector command, wherein the blended command output is computed by averaging two sorted input commands closest to a median of all the input commands;

disregarding the blended command output when deviations between the blended command output and the computed effector command exceed an established limit for a specified time;

selecting a blended command output from a plurality of blended command outputs;

comparing the selected blended command output with an effector position feedback signal; and

initiating an actuator shutdown command when deviations between the selected blended command output and the effector position feedback signal exceed an established limit for a specified time.

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